

X-STM of InAs/InGaSb/InAs/AlSb Laser Structure Interfaces: Effects of Growth Temperature*

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**Funded by the Office of Naval Research
and the Air Force Research Laboratory*

Abstract

Strained-layer heterostructures involving the 6.1 Å family of III-V semiconductors (including InAs, GaSb, and AlSb) are being investigated for use in a growing number of device applications, including mid- (3-5 μm) and long-wavelength (8-12 μm) infrared (IR) semiconductor lasers. The quality of the interfaces in these structures is expected to play a crucial role in determining device performance. Both interface roughness and inter-layer mixing are potential sources of device degradation, but it is not known which of these are present. Recently it was shown in InAs/In_{0.73}Ga_{0.28}Sb/InAs/AlSb mid-IR structures that the photoluminescence (PL) intensity and x-ray superlattice diffraction quality are strongly dependent on MBE growth temperature.¹ These characteristics were shown to be optimized within a rather narrow growth temperature range (410–460°C) and much worse outside of that range.

In this work, we present an atomic-resolution cross-sectional STM (X-STM) study of these laser structures in order to directly correlate atomic-scale features, such as interface roughness and layer intermixing, with material quality as

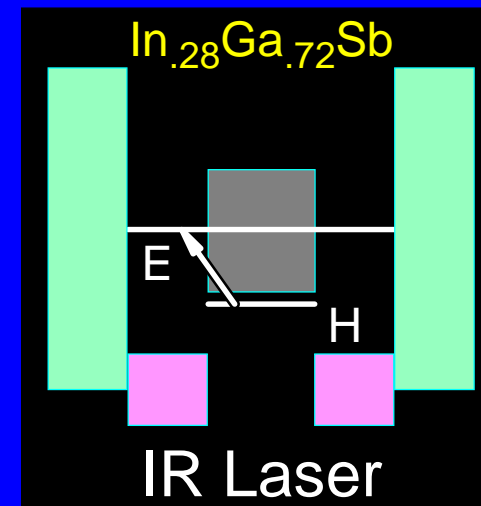
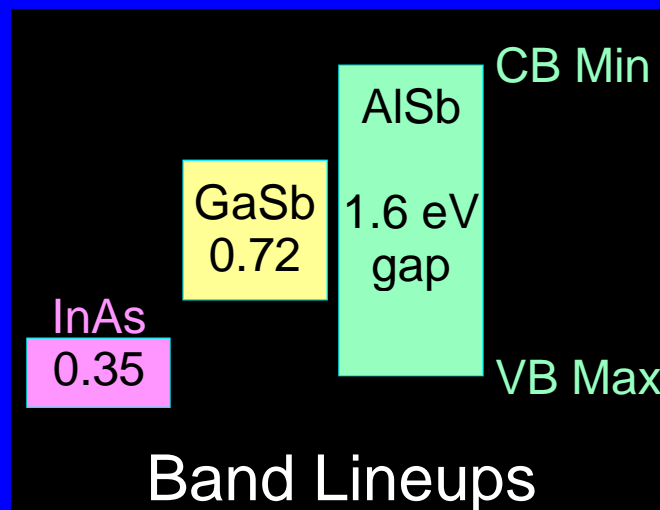
measured by PL and x-ray measurements on the same samples. Two such laser structures are compared, one grown within the optimum temperature window and another grown at higher temperatures. Overall interface roughness appears to be larger in the structure grown above the optimum temperature range. Qualitatively increased "clustering" in the InGaSb layer is also observed in the higher temperature sample. It is not known at present if the increased roughness and clustering are responsible for the observed PL and x-ray measurements.

Several features are observed, however, which are common to both high and optimum-temperature samples. Inter-mixing is observed in both empty- and filled-states images at the AlSb-on-InAs interfaces, possibly arising from either the underlying InAs or the previous InGaSb layer. Electronic structure differences are also observed in filled-states between the InAs-on-AlSb and AlSb-on-InAs interfaces. These electronic structure differences may be associated with the intermixing in the AlSb layer, or may be indicative of an interface state which may be deleterious for the material quality.

"6.1 Å" Family of III-V's: InAs, GaSb, AlSb

6.06 Å 6.10 Å 6.14 Å

- For high-speed and optoelectronic devices
 - Resonant tunneling diodes (RTD's), IR detectors, IR lasers
- Composed of superlattices and quantum-wells
 - Interfaces critical: large volume fraction of device



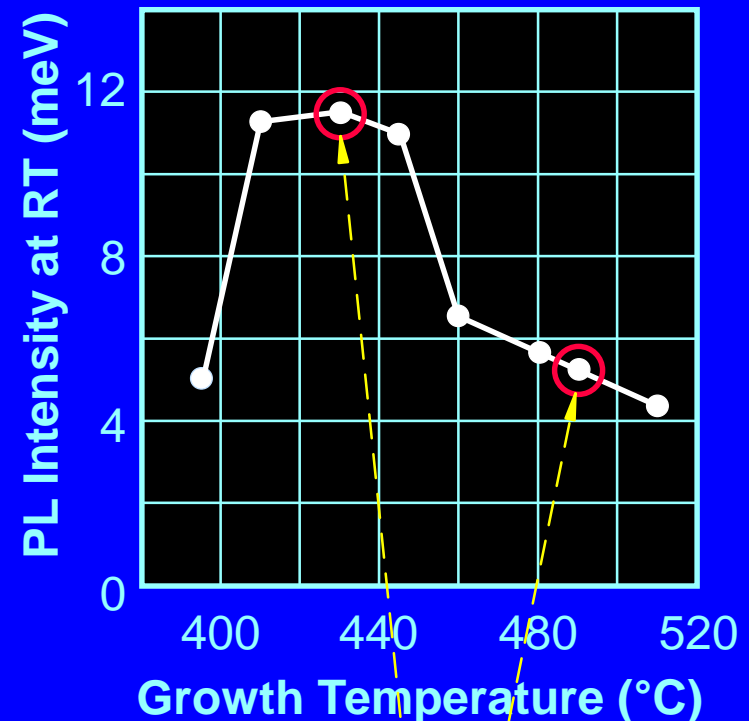
Properties sensitive to sub-ML interface variations.

Infra-Red Laser Structures

- AlSb-InAs-InGaSb-InAs Superlattice
- Dependent on growth T
- Dependent on layer thickness

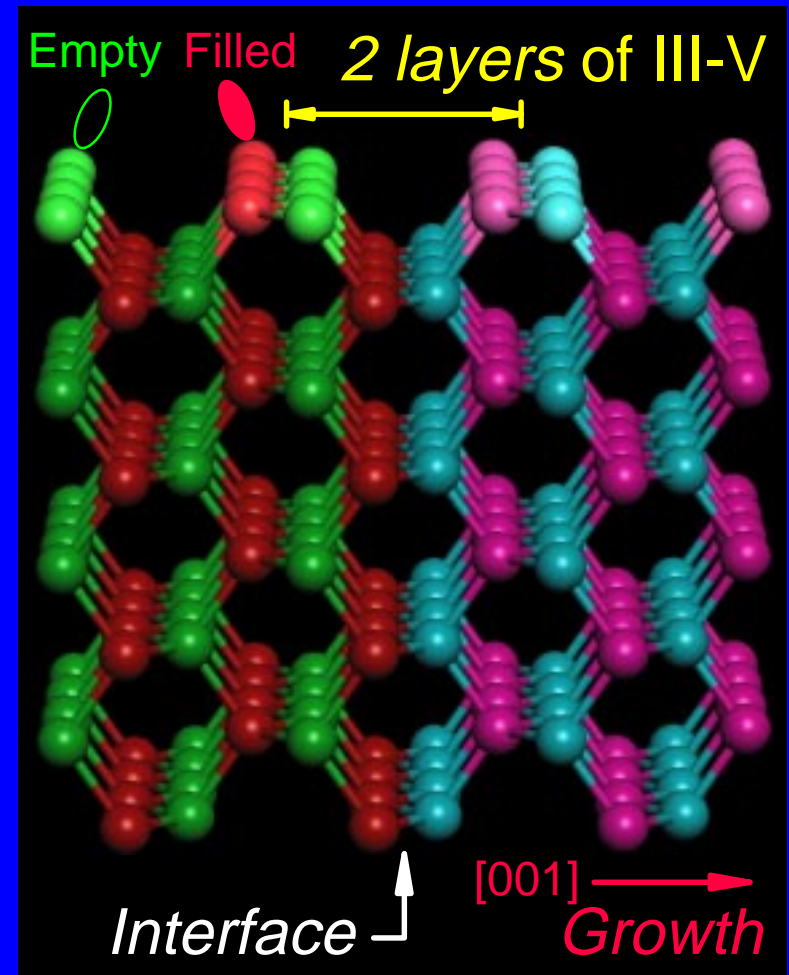
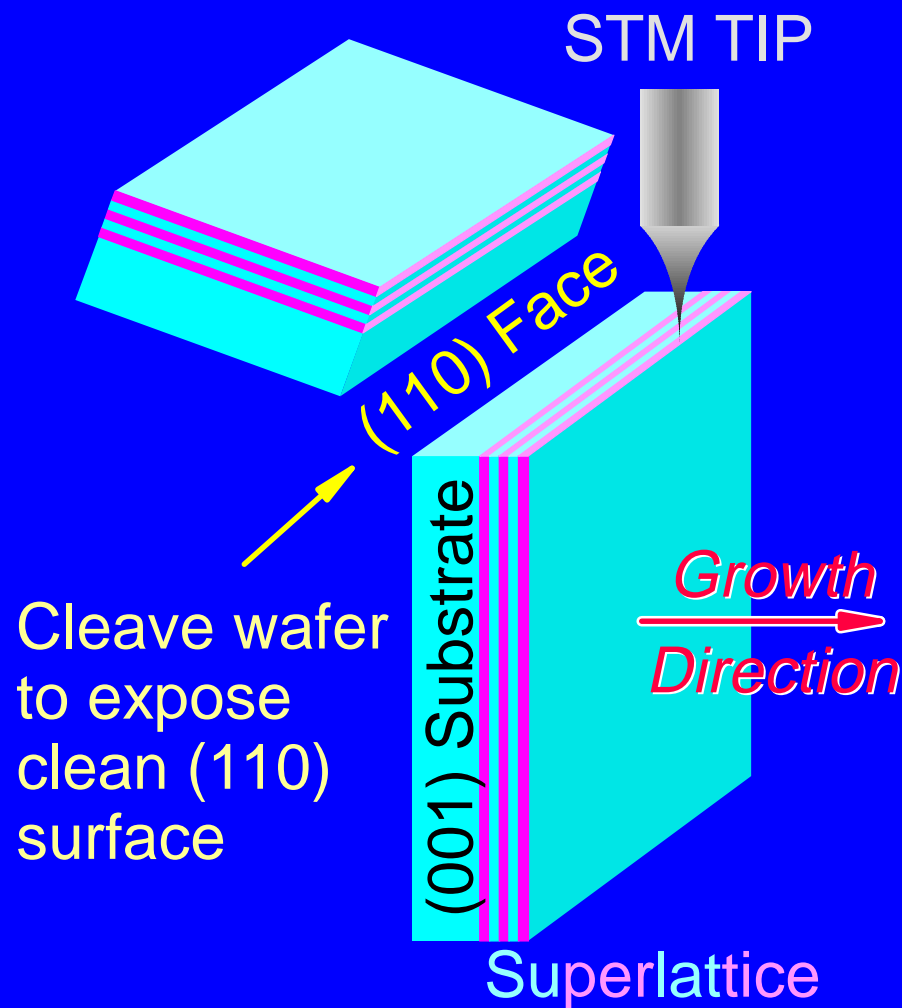
Layer Thickness (ML) vs Wavelength

AlSb	InAs	InGaSb	InAs	λ (μm)
14	7	10	7	5.8
14	6	10	6	5.1
14	5.5	10	5.5	4.4



***Samples used in
this X-STM study***

Cross-Sectional STM of (110) Surfaces



Only see every-other III (empty) or V (filled) layer.

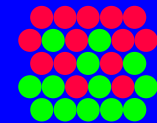
What Do We Want To Learn?

- Interface roughness – two components

- Topography: 2D vs 3D growth

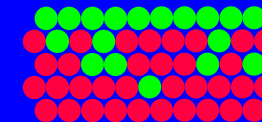
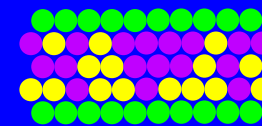


- Intermixing: during or after interface formation



- Non-Uniform Composition:

- Alloy layers (e.g. $\text{In}_x\text{Ga}_{1-x}\text{Sb}$)
- Segregation/Contamination

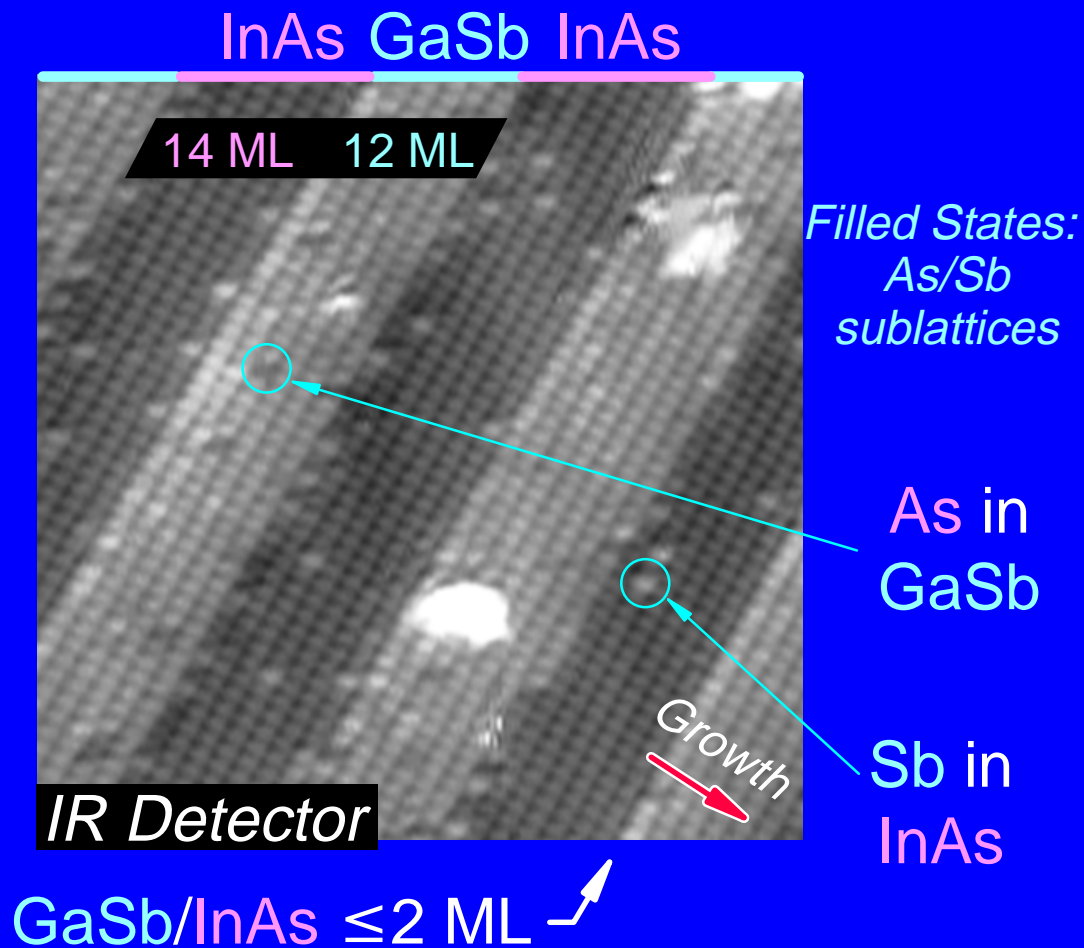


- Origins of STM contrast:

- Atomic identity and environment
- Band Structure

Can we improve MBE and Laser with X-STM?

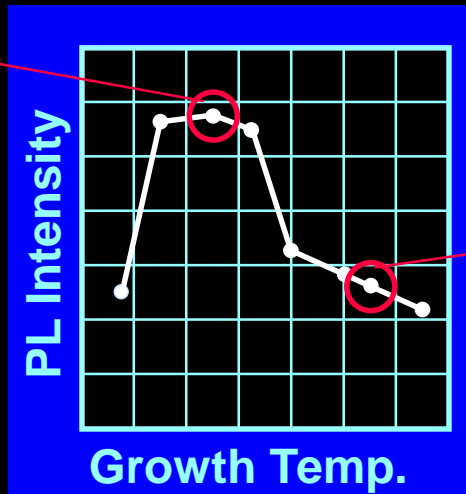
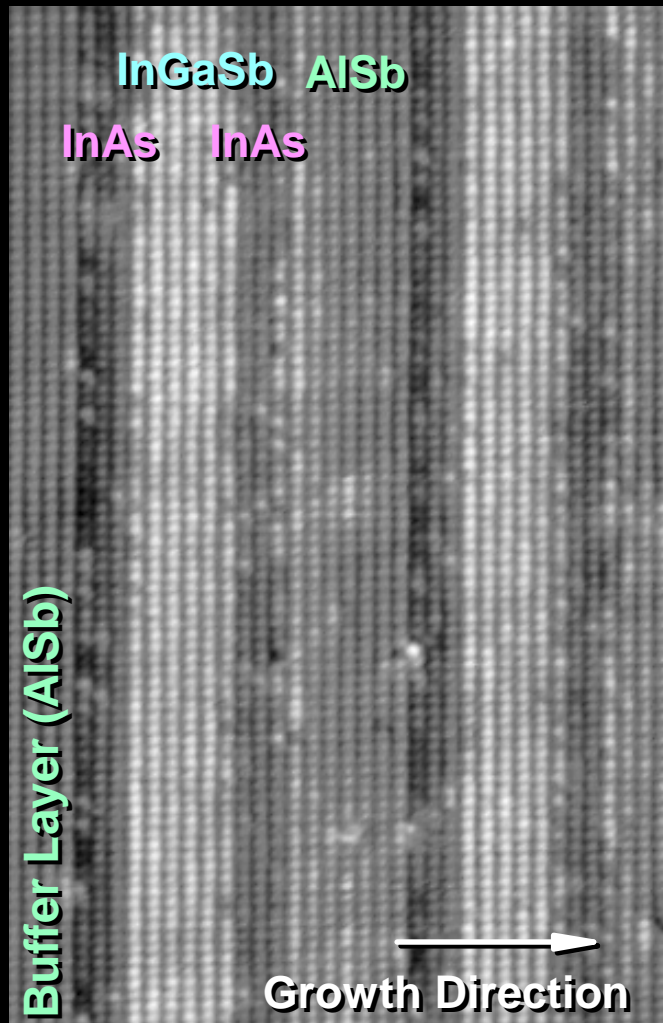
X-STM of Superlattices: Simple Example



- Atomic Resolution
- STM contrast:
entirely electronic
- Limits:
 - Every other row
 - Can miss interface

X-STM of "Good" vs. "Bad" Laser

Grown at optimum T

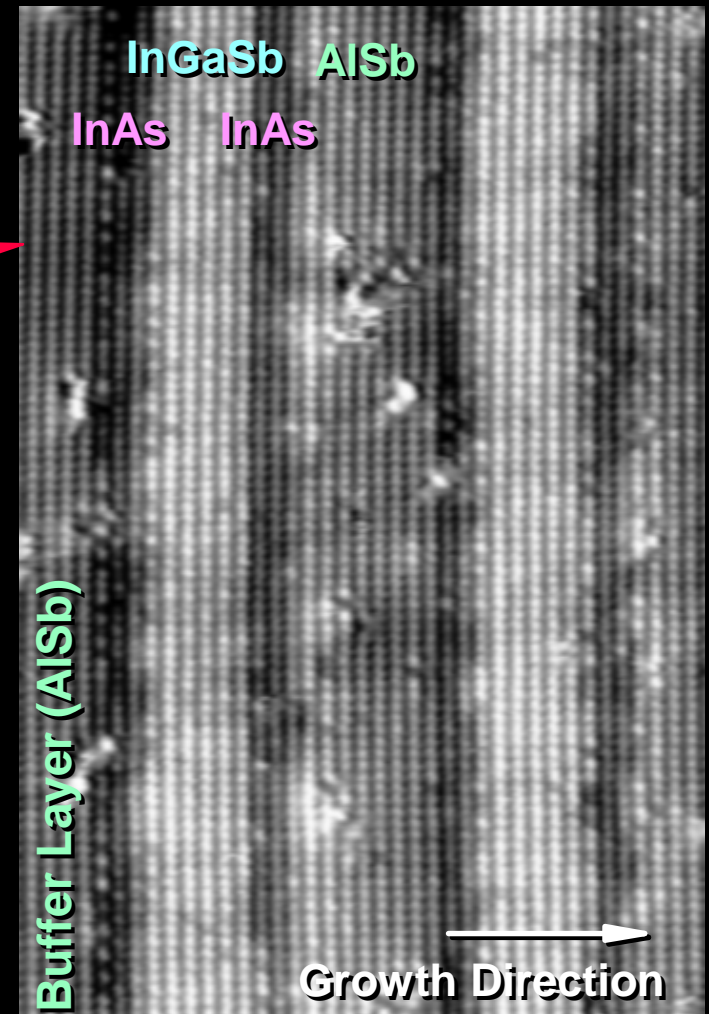


*Both grown on
the same day*

*"Device properties"
already measured*

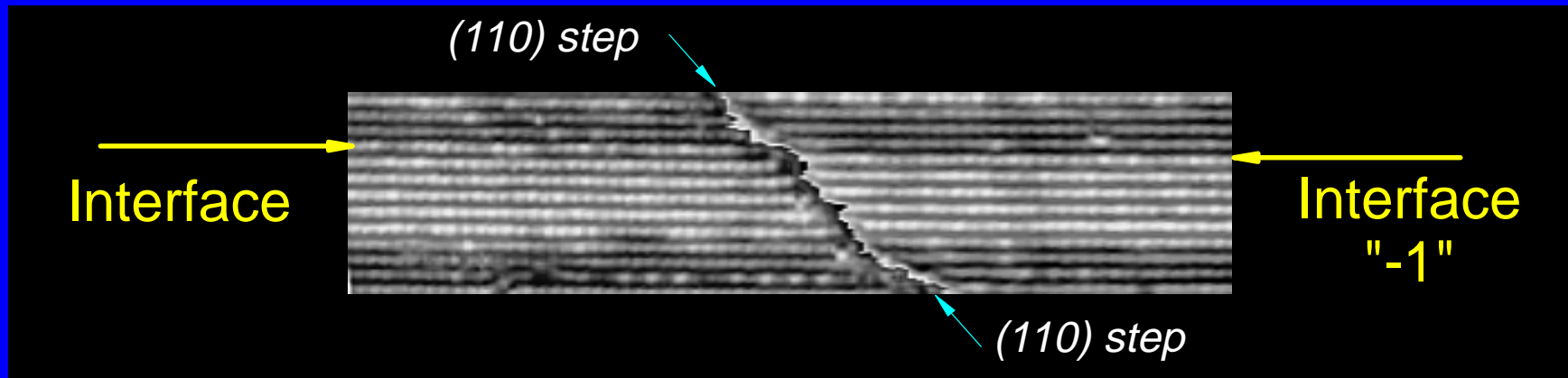
*350 Å × 230 Å
Filled States (2 V)*

Grown at higher T

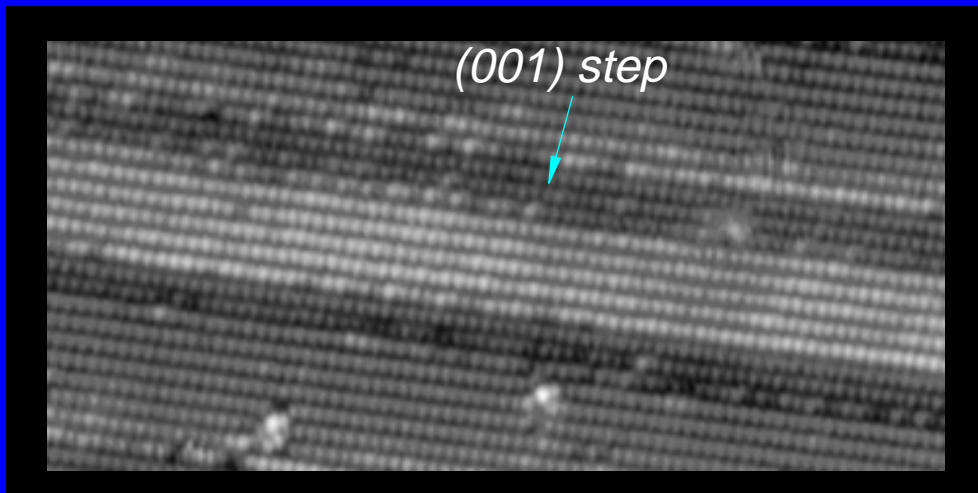


Interface Roughness: *Finding the interface*

- (110) step on cleave surface



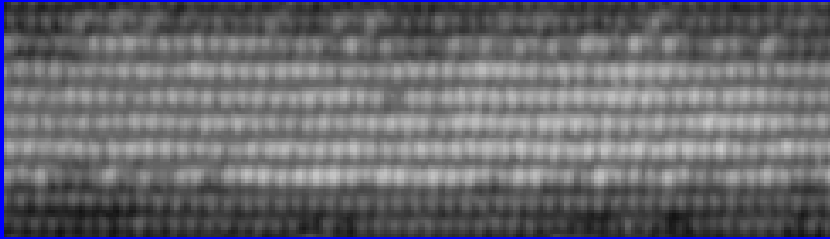
- (001) step on "growth surface"



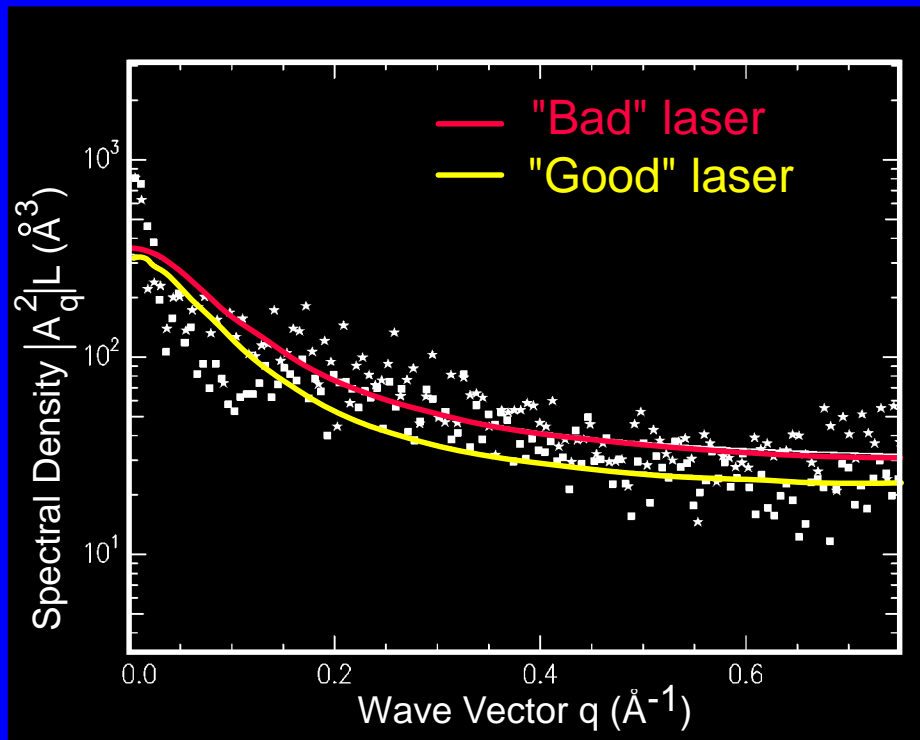
- ♦ Interface roughness is *small* (Looks almost perfect at "interface -1").
- ♦ Interface segments taken only where "spotty" interface is seen.

Interface Roughness

- Mark atoms at interface



- Power Spectrum



- Lorentzian fit:

- Interface roughness Δ
- Correlation length Λ
- "White noise" background B

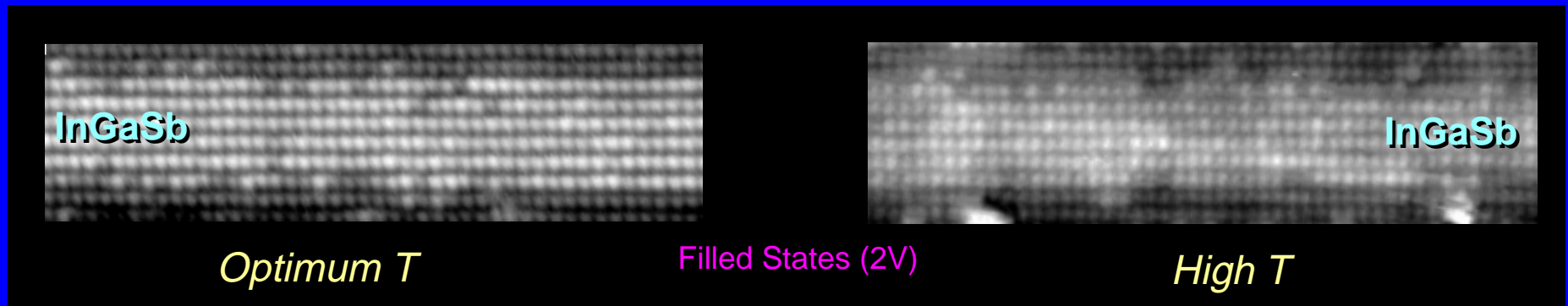
Sample	Δ (\AA)	Λ (\AA)	B (\AA^3)
"Bad"	3.7	90	28
"Good"	3.3	75	20

Analysis: Interface Roughness

- Intermixing or large-scale roughness?
 - "White noise" at interface: *Intermixing*
 - "Good" sample has smoother interfaces
- Source of intermixing
 - Exchange at surface?
Yu et al. : InGaSb/InAs "mixed As/Sb character"
 - Thermal interdiffusion?
- Bad enough to screw up device?
 - Not a large difference
 - Preliminary TEM (M. Twigg): dislocations at high T

Composition Non-Uniformities

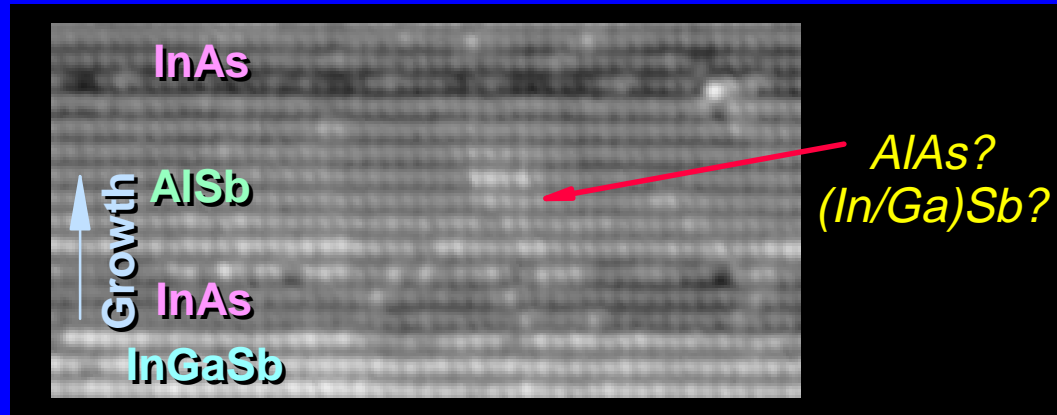
- InGaSb layer: Clustering



- Increased 'clusters' in high-T laser samples
- Effect on electronic properties:
 - PL line broadening
 - PL intensity: reduced

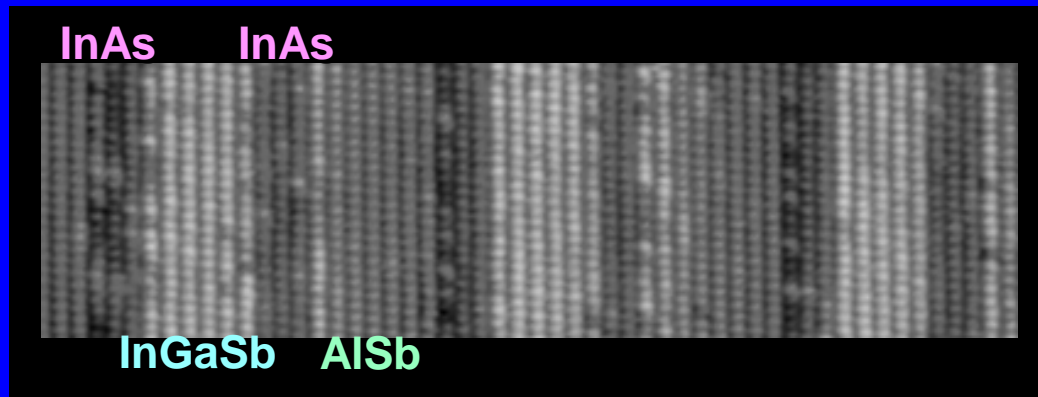
Composition Non-Uniformities

- AlSb layer: 'Contamination'



- Identity of contaminants?
- Effect on electronic properties of material?

- InAs layers: Growth order dependence

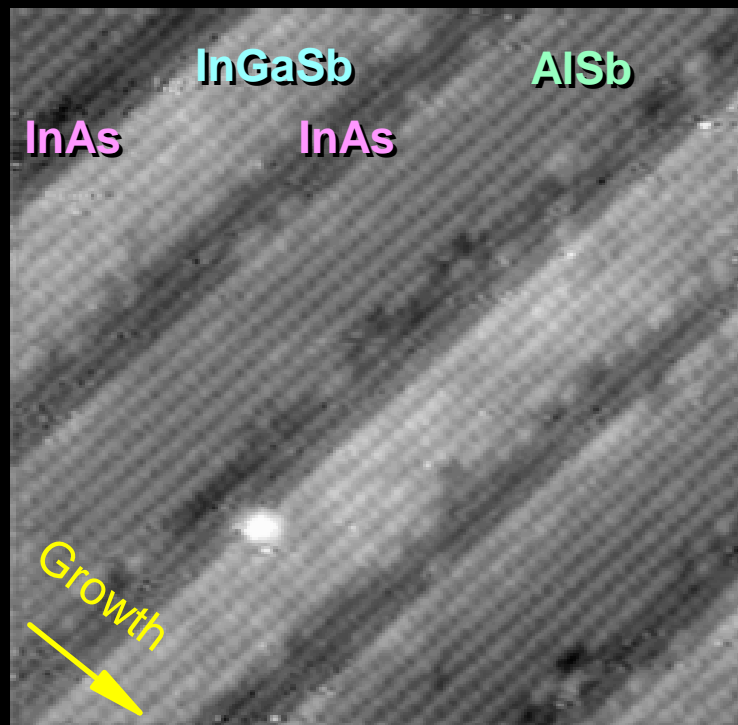


- Alternating "light" and "dark"
- Source:
 - Interface state, from different bond type? (InSb vs AlSb)
 - Contamination at InAs/AlSb interface?

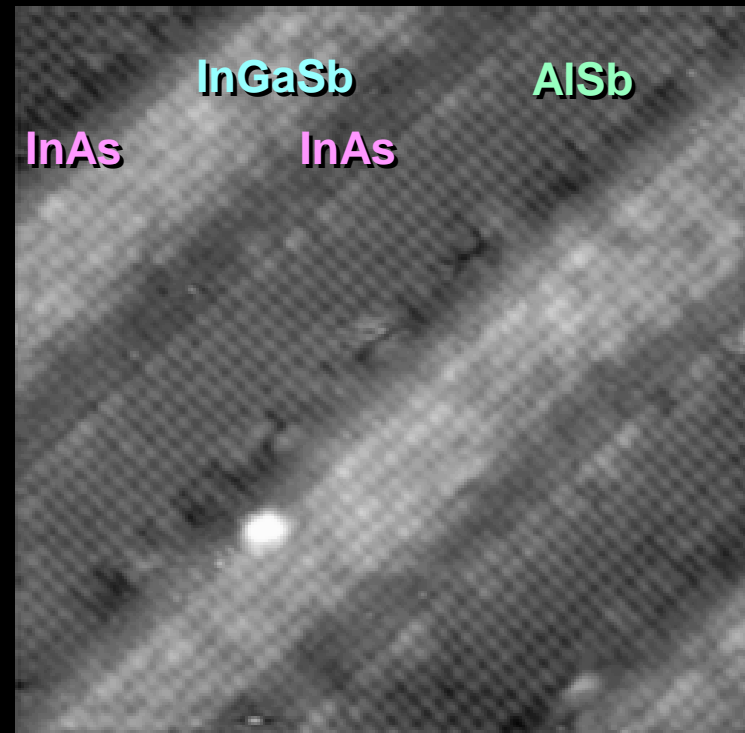
'Good' laser sample: Dual Bias Imaging

- 'Contamination' and growth-order dependence seen in both empty and filled states

Filled States (2.5 V bias)



Empty States (2.0 V bias)



225 Å x 225 Å

Summary

Implications for Material Quality

- Interface roughness measurement:
 - More intermixing at InAs/InGaSb interface: high-T sample
 - Insufficient to account for PL?
 - Other length scales more relevant? (M. Twigg, TEM results)
- Observation of composition non-uniformities:
 - Increased 'clustering' in InGaSb layer
 - Contamination in AlSb layer
 - InAs alternating contrast: "defect state" at interface?
- Future:
 - Low T sample, As-bonded sample (defect-free from TEM)
 - Quantitative comparison with first-principles (L. Hemstreet)